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(54) **SYSTEMS AND METHODS FOR IMPROVING REPRESENTATION BY AN AUDITORY PROSTHESIS SYSTEM OF AUDIO SIGNALS HAVING INTERMEDIATE SOUND LEVELS**

(75) Inventors: **Leonid M. Litvak**, Los Angeles, CA (US); **Nobutaka Okuyama**, Valencia, CA (US); **Abhijit Kulkarni**, Newbury Park, CA (US)

(73) Assignee: **Advanced Bionics AG**, Staefa (CH)

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CPC ..... **H04R 25/50** (2013.01); **A61N 1/0541** (2013.01); **A61N 1/36032** (2013.01); **H03G 3/20** (2013.01)

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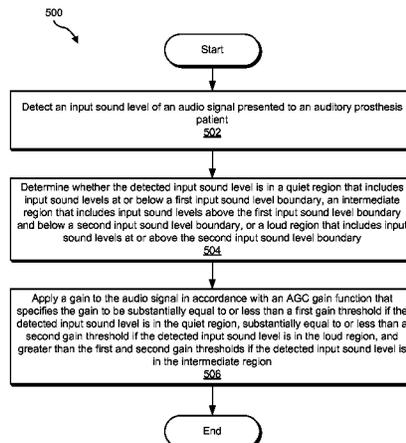
*Primary Examiner* — Edgar Guerra-Erazo

(74) *Attorney, Agent, or Firm* — ALG Intellectual Property, LLC

(57) **ABSTRACT**

An exemplary system includes a detection facility configured to detect an input sound level of an audio signal presented to an auditory prosthesis patient; and an adaptive gain control (AGC) facility configured to 1) determine whether the detected input sound level is in a quiet region, an intermediate region, or a loud region, and 2) apply a gain to the audio signal in accordance with an AGC gain function that specifies the gain to be substantially equal to or less than a first gain threshold if the detected input sound level is in the quiet region, substantially equal to or less than a second gain threshold if the detected input sound level is in the loud region, and greater than the first and second gain thresholds if the detected input sound level is in the intermediate region. Corresponding systems and methods are also disclosed.

**20 Claims, 11 Drawing Sheets**



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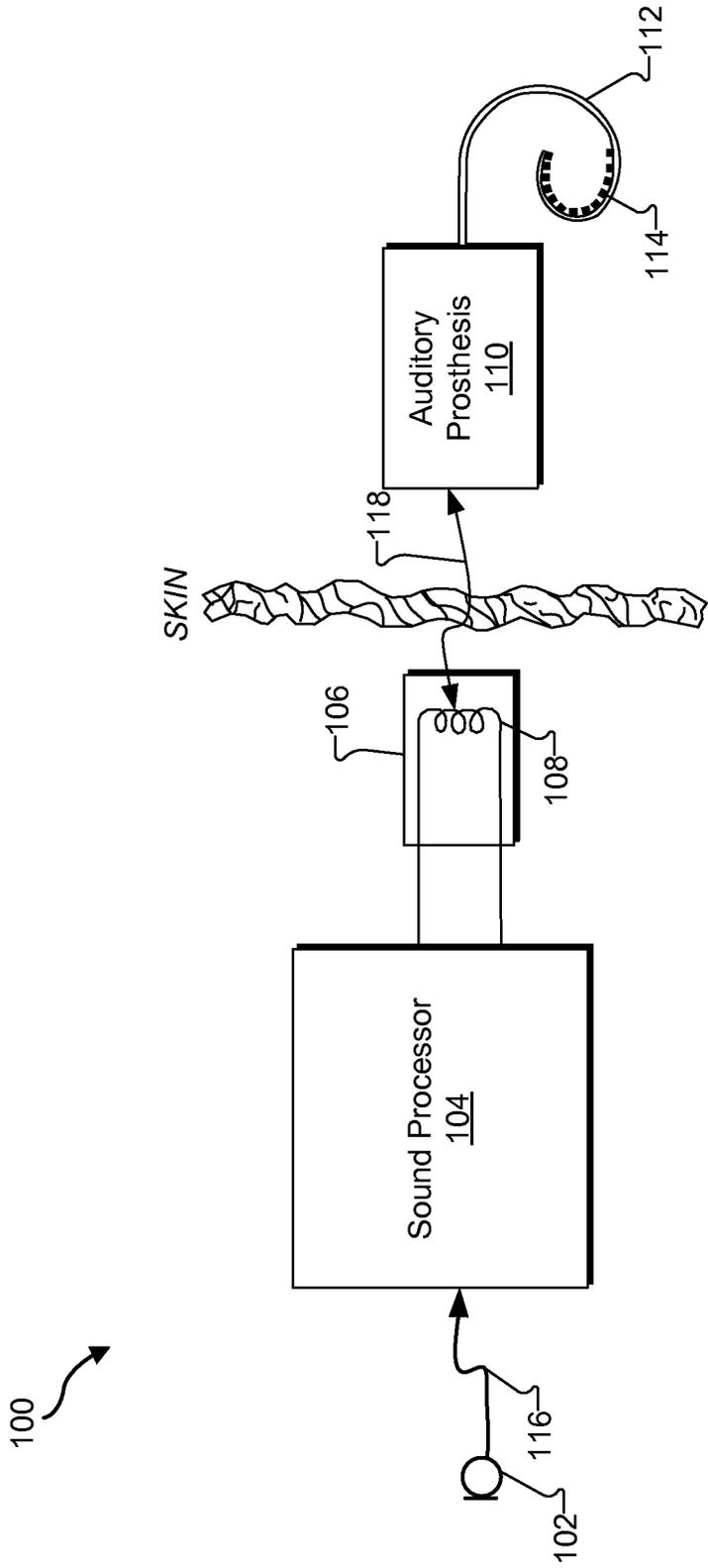
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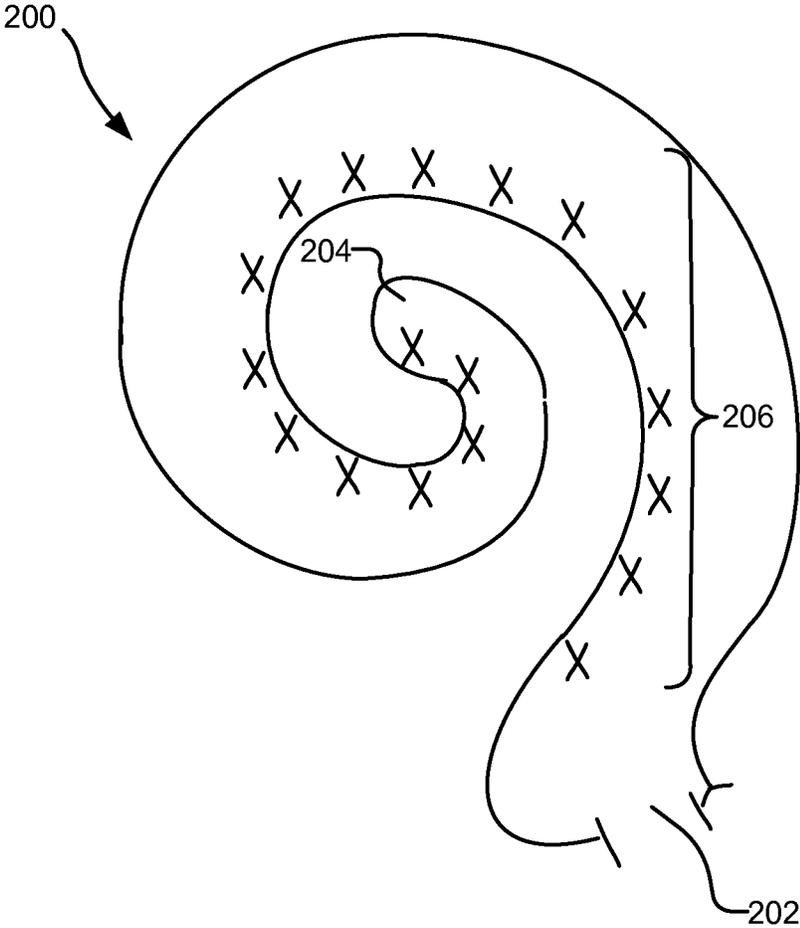
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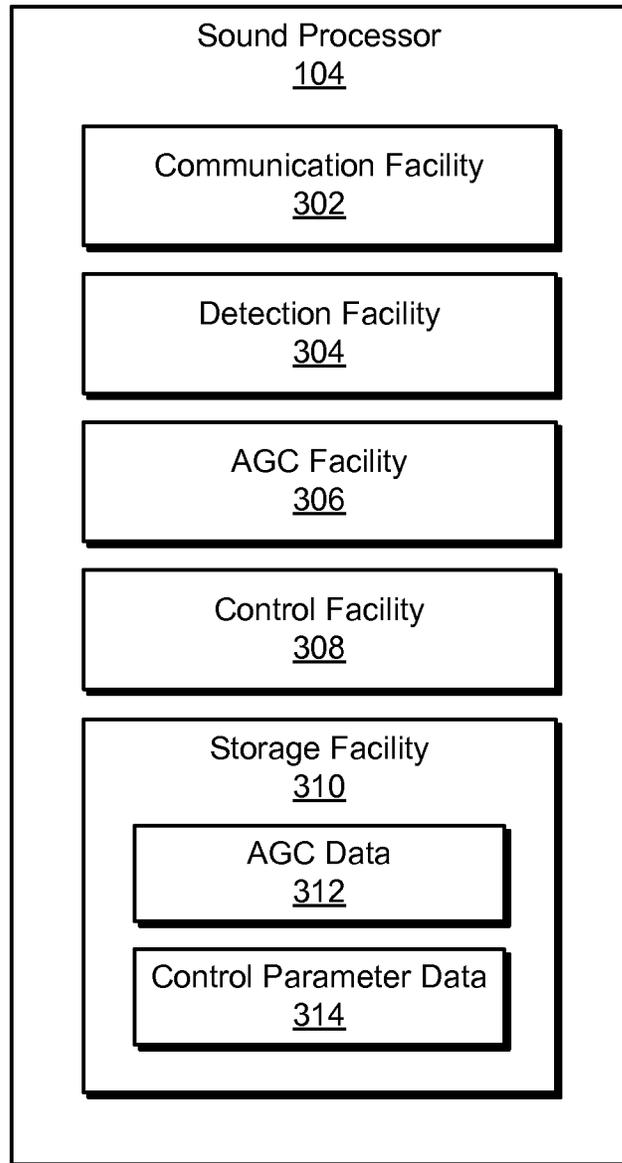
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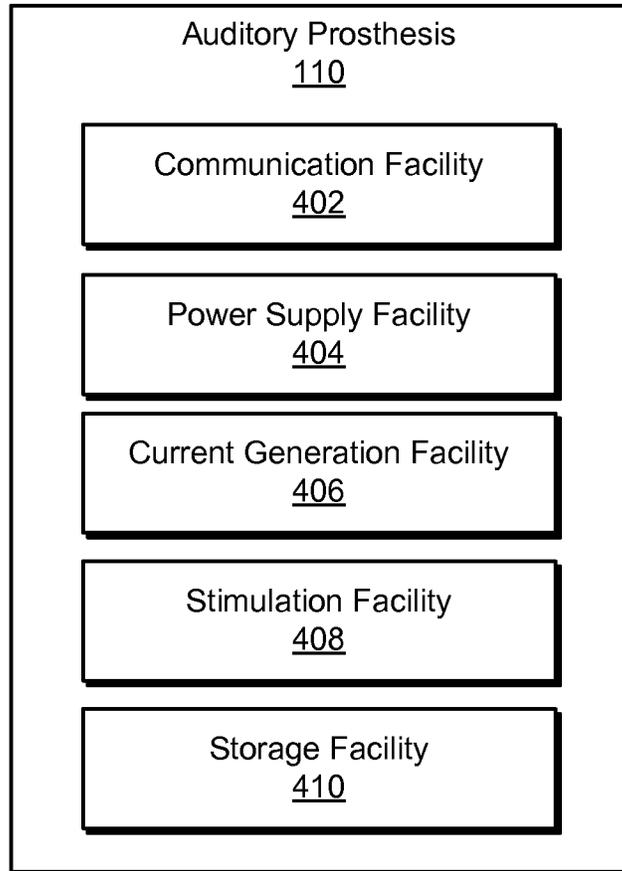
**Fig. 1**



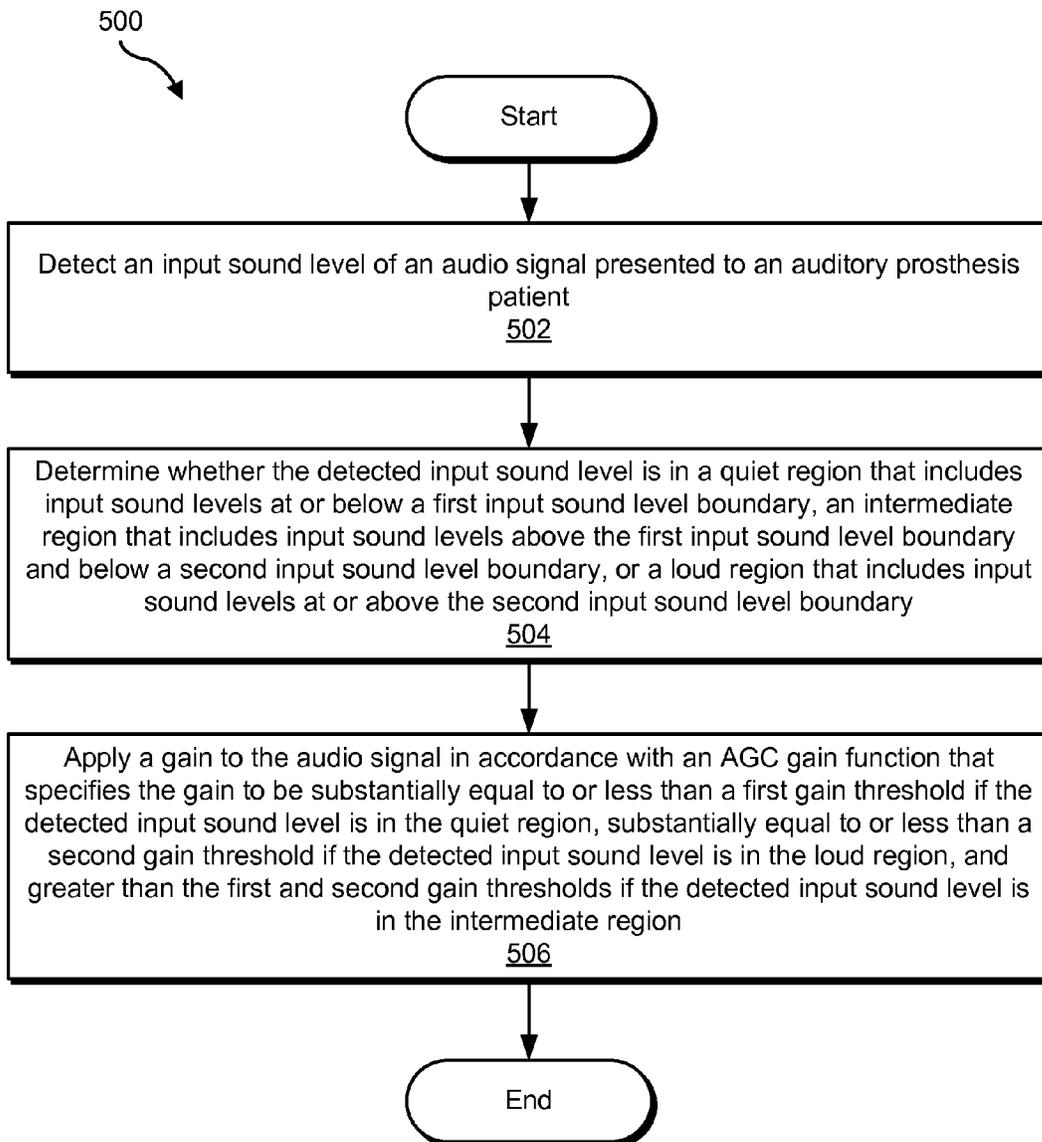
**Fig. 2**



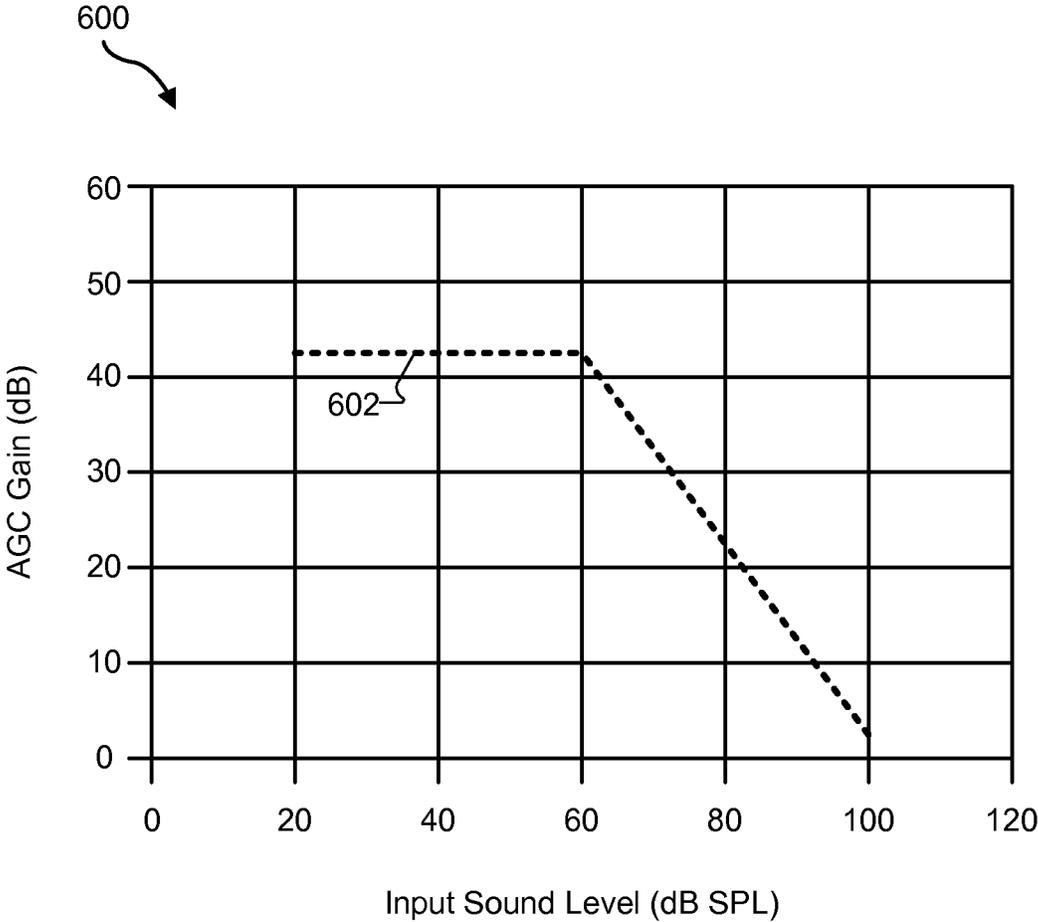
**Fig. 3**



**Fig. 4**

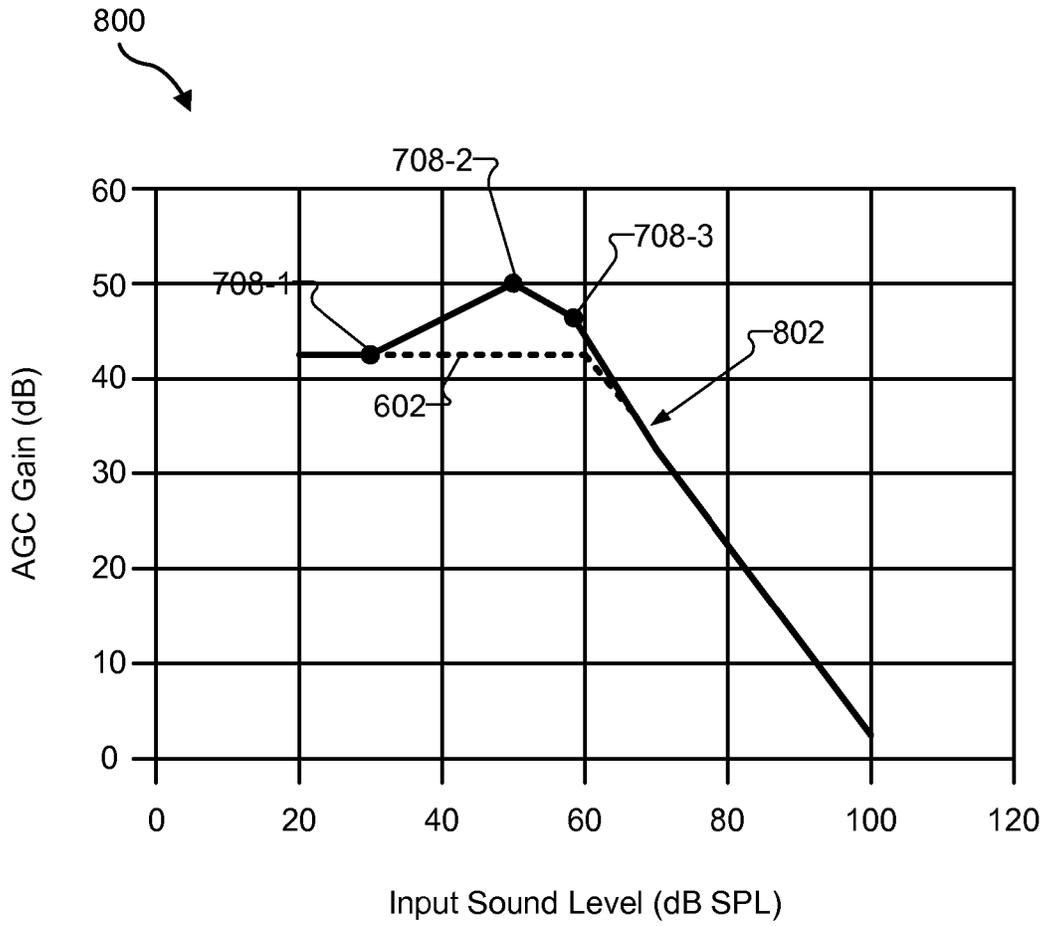


**Fig. 5**

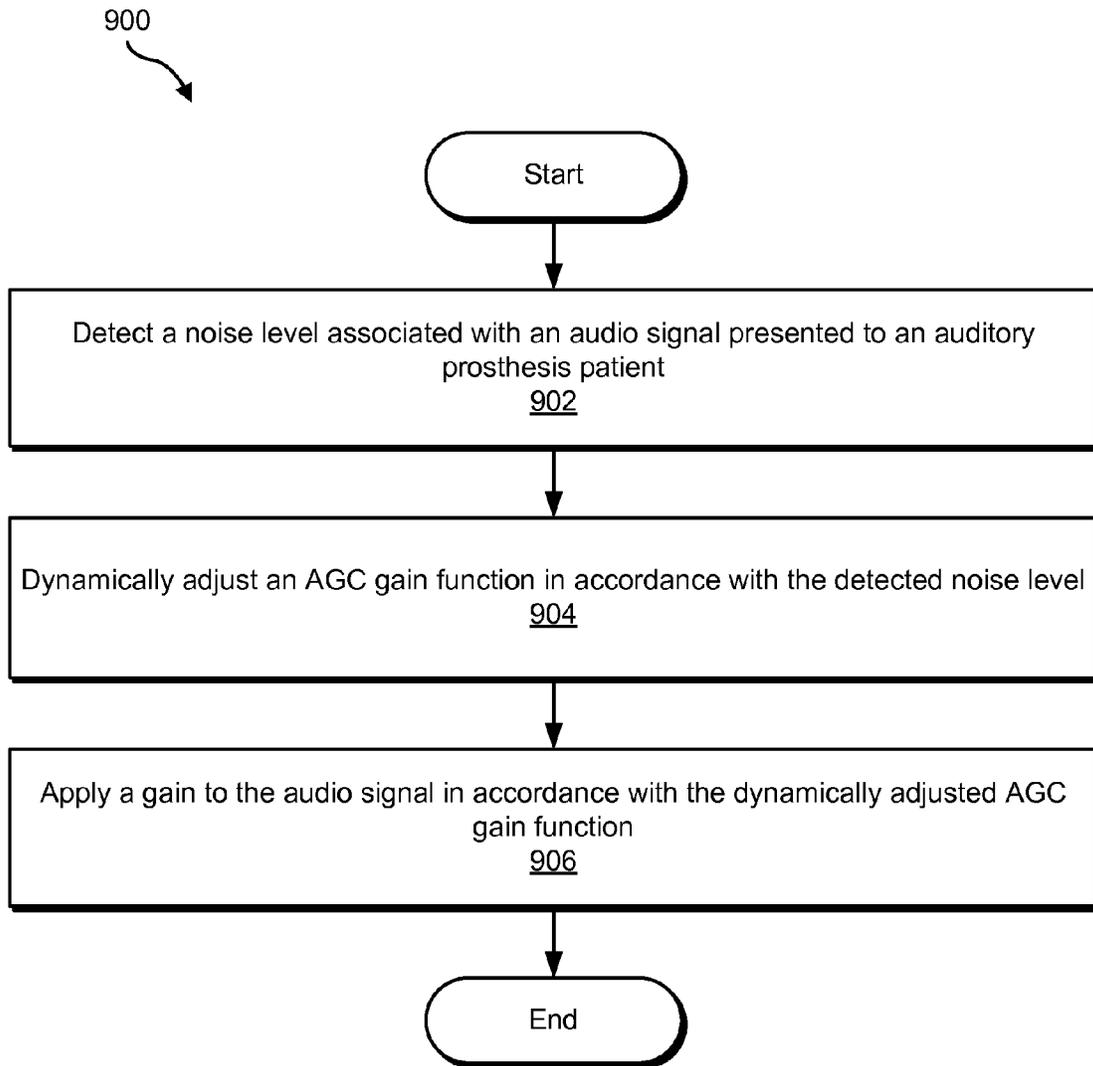


**Fig. 6**

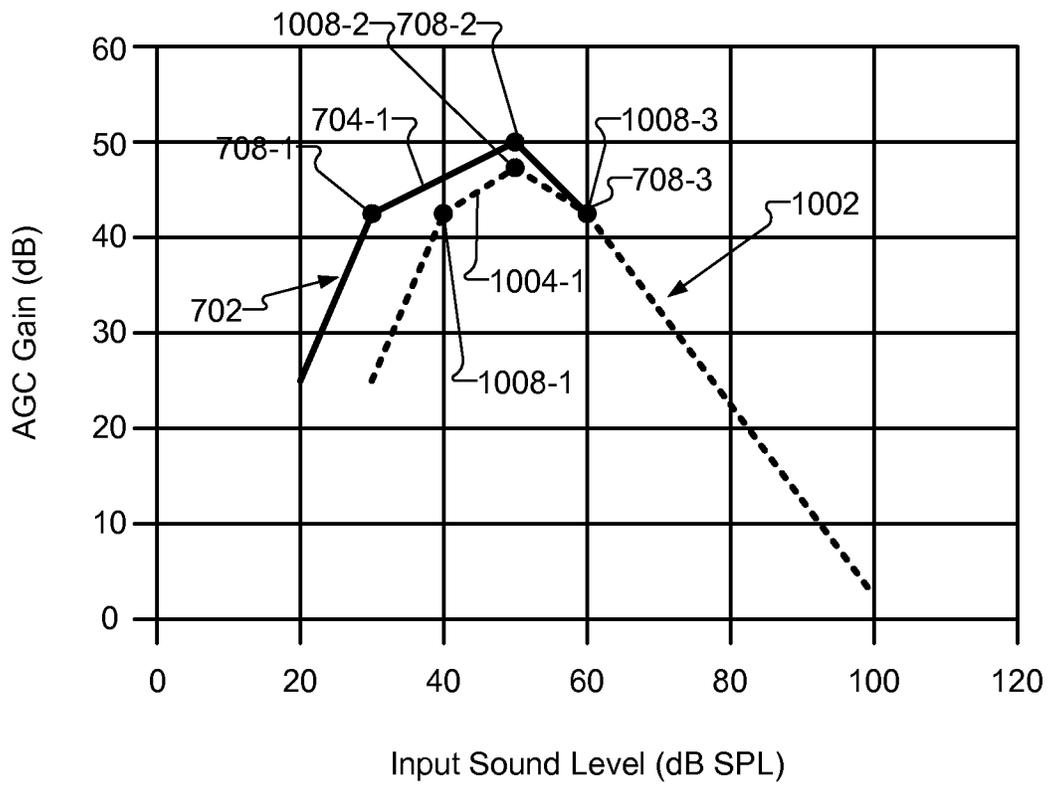




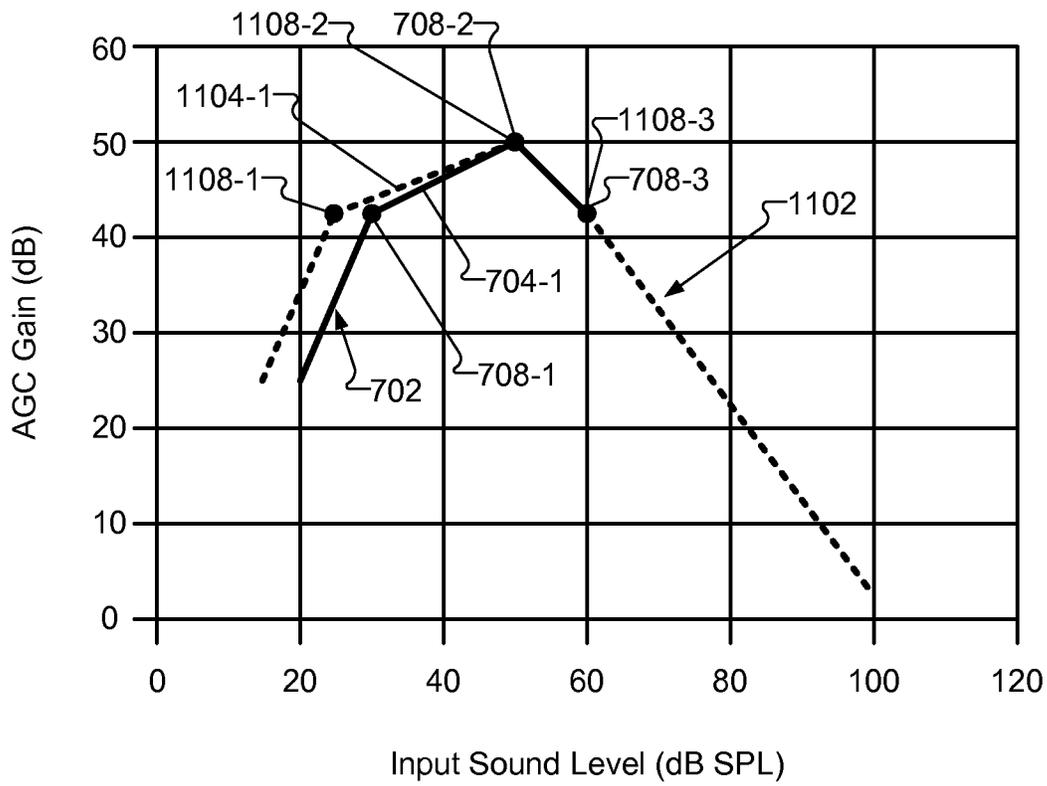
**Fig. 8**



**Fig. 9**



**Fig. 10**



**Fig. 11**

# SYSTEMS AND METHODS FOR IMPROVING REPRESENTATION BY AN AUDITORY PROSTHESIS SYSTEM OF AUDIO SIGNALS HAVING INTERMEDIATE SOUND LEVELS

## BACKGROUND INFORMATION

Auditory prosthesis patients (e.g., cochlear implant patients) often have trouble understanding relatively quiet sounds, such as soft speech. Traditional auditory prosthesis systems attempt to overcome this limitation by amplifying audio signals presented to auditory prosthesis patients before the signals are otherwise processed. However, in order to prevent already loud sounds from being further amplified, many auditory prosthesis systems use adaptive gain control (“AGC”) to selectively amplify sounds below a predetermined input sound level (e.g., 60 dB SPL) and compress sounds above the predetermined input sound level.

Unfortunately, adaptive gain control also amplifies undesirable sounds, or noise, present below the predetermined input sound level. For example, environmental noise, system noise (e.g., microphone noise), and other types of noise are often present within the 20-40 dB SPL range, while soft speech is often within the 40-50 dB SPL range. In these situations, traditional adaptive gain control amplifies both the soft speech and the noise, thereby making it even more difficult, in some instances, for a patient to understand the soft speech.

## BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings illustrate various embodiments and are a part of the specification. The illustrated embodiments are merely examples and do not limit the scope of the disclosure. Throughout the drawings, identical or similar reference numbers designate identical or similar elements.

FIG. 1 illustrates an exemplary auditory prosthesis system according to principles described herein.

FIG. 2 illustrates a schematic structure of the human cochlea.

FIG. 3 illustrates exemplary components of a sound processor according to principles described herein.

FIG. 4 illustrates exemplary components of an auditory prosthesis according to principles described herein.

FIG. 5 illustrates an exemplary method of improving representation by an auditory prosthesis system of audio signals having intermediate sound levels according to principles described herein.

FIGS. 6-8 show various exemplary AGC gain functions according to principles described herein.

FIG. 9 illustrates another exemplary method of improving representation by an auditory prosthesis system of audio signals having intermediate sound levels according to principles described herein.

FIG. 10 shows an adjusted AGC gain function that may be derived by decreasing a range of an expansion phase according to principles described herein.

FIG. 11 shows an adjusted AGC gain function that may be derived by increasing a range of an expansion phase according to principles described herein.

## DETAILED DESCRIPTION

Systems and methods for improving representation by an auditory prosthesis system of audio signals having intermediate sound levels are described herein. As will be described in more detail below, the systems and methods described

herein may facilitate improved understanding by an auditory prosthesis patient of soft speech and other audio signals of interest (e.g., music, etc.) that fall within an intermediate input sound level range compared to low level noise and relatively loud sounds.

To this end, as will be described in more detail below, a speech processor communicatively coupled to an auditory prosthesis (e.g., a cochlear implant) that may be implanted within a patient may detect an input sound level of an audio signal presented to the patient. The speech processor may then determine whether the detected input sound level falls within a quiet region (i.e., a region that includes input sound levels at or below a first input sound level boundary), an intermediate region (i.e., a region that includes input sound levels above the first input sound level boundary and below a second input sound level boundary), or a loud region (e.g., a region that includes input sound levels at or above the second input sound level boundary). The speech processor may then apply a gain to the audio signal in accordance with an AGC gain function that specifies or sets the gain to be substantially equal to or less than a first gain threshold if the detected input sound level is in the quiet region, substantially equal to or less than a second gain threshold if the detected input sound level is in the loud region, and greater than the first and second gain thresholds if the detected input sound level is in the intermediate region.

To illustrate, the quiet region may be designated to include input sound levels at or below 30 dB SPL (a typical noise floor), the intermediate region may be designated to include input sound levels between 30 dB SPL and 60 dB SPL (a typical region in which soft speech may be present), and the loud region may be designated to include input sound levels at or above 60 dB SPL (a typical region of relatively loud sounds). With these designations in place, soft speech and other sounds that fall within the intermediate region may be amplified while the loudness level of audio signals that comprise noise and loud sounds may be either maintained or compressed. In this manner, an auditory prosthesis patient may more effectively perceive and/or understand soft speech.

In some examples, the AGC gain function used to apply gain to audio signals presented to an auditory prosthesis patient may be dynamically adjusted in response to one or more factors. For example, a speech processor may detect a noise level associated with an audio signal presented to an auditory prosthesis patient and dynamically adjust an AGC gain function in accordance with the detected noise level. The speech processor may then apply a gain to the audio signal in accordance with the adjusted AGC gain function.

To illustrate, a speech processor may detect an increase in noise that may result from an auditory prosthesis patient moving from one environment to another. In response, the sound processor may decrease a range of an expansion phase (described in detail below) included in the AGC gain function to account for the increase in noise. In this manner, as will be described in more detail below, the speech processor may prevent the increased noise from being amplified along with the audio signal of interest.

FIG. 1 illustrates an exemplary auditory prosthesis system 100. Auditory prosthesis system 100 may include a microphone 102, a sound processor 104, a headpiece 106 having a coil 108 disposed therein, an auditory prosthesis 110, and a lead 112 with a plurality of electrodes 114 disposed thereon. Additional or alternative components may be included within auditory prosthesis system 100 as may serve a particular implementation.

As shown in FIG. 1, microphone 102, sound processor 104, and headpiece 106 may be located external to an auditory

prosthesis patient. In some alternative examples, microphone **102** and/or sound processor **104** may be implanted within the patient. In such configurations, the need for headpiece **106** may be obviated.

Microphone **102** may detect an audio signal and convert the detected signal to a corresponding electrical signal. The electrical signal may be sent from microphone **102** to sound processor **104** via a communication link **116**, which may include a telemetry link, a wire, and/or any other suitable communication link.

Sound processor **104** is configured to direct auditory prosthesis **110** to generate and apply electrical stimulation (also referred to herein as “stimulation current”) to one or more stimulation sites associated with an auditory pathway (e.g., the auditory nerve) of the patient. Exemplary stimulation sites include, but are not limited to, one or more locations within the cochlea, the cochlear nucleus, the inferior colliculus, and/or any other nuclei in the auditory pathway. To this end, sound processor **104** may process the audio signal detected by microphone **102** in accordance with a selected sound processing strategy to generate appropriate stimulation parameters for controlling auditory prosthesis **110**.

Sound processor **104** may be further configured to transcutaneously transmit one or more control parameters and/or one or more power signals to auditory prosthesis **110** with coil **108** by way of a communication link **118**. These control parameters may be configured to specify one or more stimulation parameters, operating parameters, and/or any other parameter by which auditory prosthesis **110** is to operate as may serve a particular implementation. Exemplary control parameters include, but are not limited to, stimulation current levels, volume control parameters, program selection parameters, operational state parameters (e.g., parameters that turn a sound processor and/or an auditory prosthesis on or off), audio input source selection parameters, fitting parameters, noise reduction parameters, microphone sensitivity parameters, microphone direction parameters, pitch parameters, timbre parameters, sound quality parameters, most comfortable current levels (“M levels”), threshold current levels, channel acoustic gain parameters, front and backend dynamic range parameters, current steering parameters, pulse rate values, pulse width values, frequency parameters, amplitude parameters, waveform parameters, electrode polarity parameters (i.e., anode-cathode assignment), location parameters (i.e., which electrode pair or electrode group receives the stimulation current), stimulation type parameters (i.e., monopolar, bipolar, or tripolar stimulation), burst pattern parameters (e.g., burst on time and burst off time), duty cycle parameters, spectral tilt parameters, filter parameters, and dynamic compression parameters. Sound processor **104** may also be configured to operate in accordance with one or more of the control parameters.

Sound processor **104** may include or be implemented by a behind-the-ear (“BTE”) unit, a body-worn portable speech processor (“PSP”), and/or any other sound processing unit as may serve a particular implementation. Exemplary components of sound processor **104** will be described in more detail below.

As shown in FIG. 1, coil **108** may be housed within headpiece **106**, which may be affixed to a patient’s head and positioned such that coil **108** is communicatively coupled to a corresponding coil included within auditory prosthesis **110**. In this manner, control parameters and power signals may be wirelessly transmitted between sound processor **104** and auditory prosthesis **110** via communication link **118**. It will be understood that data communication link **118** may include a bi-directional communication link and/or one or more dedi-

cated uni-directional communication links. In some alternative embodiments, sound processor **104** and auditory prosthesis **110** may be directly connected with one or more wires or the like.

Auditory prosthesis **110** may include any type of implantable stimulator that may be used in association with the systems and methods described herein. For example, auditory prosthesis **110** may include an implantable cochlear stimulator. In some alternative implementations, auditory prosthesis **110** may include a brainstem implant and/or any other type of auditory prosthesis that may be implanted within a patient and configured to apply stimulation to one or more stimulation sites located along an auditory pathway of a patient.

In some examples, auditory prosthesis **110** may be configured to generate electrical stimulation representative of an audio signal detected by microphone **102** in accordance with one or more stimulation parameters transmitted thereto by sound processor **104**. Auditory prosthesis **110** may be further configured to apply the electrical stimulation to one or more stimulation sites within the patient via one or more electrodes **114** disposed along lead **112**. In some examples, auditory prosthesis **110** may include a plurality of independent current sources each associated with a channel defined by one or more of electrodes **114**. In this manner, different stimulation current levels may be applied to multiple stimulation sites simultaneously by way of multiple electrodes **114**. In such examples, auditory prosthesis system **100** may be referred to as a “multi-channel auditory prosthesis system.”

To facilitate application of the electrical stimulation generated by auditory prosthesis **110**, lead **112** may be inserted within a duct of the cochlea such that electrodes **114** are in communication with one or more stimulation sites within the cochlea. FIG. 2 illustrates a schematic structure of the human cochlea **200** into which lead **112** may be inserted. As shown in FIG. 2, the cochlea **200** is in the shape of a spiral beginning at a base **202** and ending at an apex **204**. Within the cochlea **200** resides auditory nerve tissue **206**, which is denoted by Xs in FIG. 2. The auditory nerve tissue **206** is organized within the cochlea **200** in a tonotopic manner. Low frequencies are encoded at the apex **204** of the cochlea **200** while high frequencies are encoded at the base **202**. Hence, each location along the length of the cochlea **200** corresponds to a different perceived frequency. Auditory prosthesis system **100** may therefore be configured to apply electrical stimulation to different locations within the cochlea **200** (e.g., different locations along the auditory nerve tissue **206**) to provide a sensation of hearing.

Alternatively, lead **112** may be implanted within a patient such that electrodes **114** are in communication with one or more stimulation sites otherwise located along the auditory pathway. As used herein, the term “in communication with” refers to electrodes **114** being adjacent to, in the general vicinity of, in close proximity to, directly next to, or directly on the stimulation site. Any number of electrodes **114** (e.g., sixteen) may be disposed on lead **112** as may serve a particular implementation.

FIG. 3 illustrates exemplary components of sound processor **104**. As shown in FIG. 3, sound processor **104** may include a communication facility **302**, a detection facility **304**, an AGC facility **306**, a control facility **308**, and a storage facility **310**, which may be in communication with one another using any suitable communication technologies. Each of these facilities **302-310** may include any combination of hardware, software, and/or firmware as may serve a particular implementation. For example, one or more of facilities **302-310** may include at least one computing device or pro-

cessor configured to perform one or more of the functions described herein. Facilities **302-310** will now be described in more detail.

Communication facility **302** may be configured to facilitate communication between sound processor **104** and auditory prosthesis **110**. For example, communication facility **302** may include transceiver components configured to wirelessly transmit data (e.g., control parameters and/or power signals) to auditory prosthesis **110** and/or wirelessly receive data from auditory prosthesis **110**.

Detection facility **304** may be configured to detect an audio signal presented to an auditory prosthesis patient and one or more attributes associated therewith. For example, detection facility **304** may detect an input sound level of an audio signal presented to an auditory prosthesis patient. The input sound level of an audio signal may be represented in dB SPL, for example, and may be detected in any suitable manner.

Additionally or alternatively, detection facility **304** may detect a noise level associated with an audio signal presented to an auditory prosthesis patient. Detection facility **304** may detect the noise level using any suitable noise detection heuristic.

In some examples, detection facility **304** may detect a noise level associated with an audio signal by detecting a noise level of a noise signal presented to the auditory prosthesis patient concurrently with the audio signal. The noise signal may include ambient noise generated from the environment in which the patient is located, bodily noises (e.g., the patient's heartbeat), noise generated by any component of auditory prosthesis system **100**, and/or any other type of noise as may serve a particular implementation. It will be recognized that, in some instances, detection facility **304** may detect a single composite signal comprising both the audio signal and the noise signal (e.g., a signal comprising a speech component and a noise component). Detection facility **304** may be configured to process the composite signal and separate out the noise signal (e.g., the noise component) and the audio signal of interest (e.g., the speech component) in accordance with any suitable noise detection heuristic as may serve a particular implementation.

Alternatively, detection facility **304** may detect a noise level associated with an audio signal by detecting an environment in which the auditory prosthesis patient is located and setting the noise level to be equal to a predetermined noise level associated with the detected environment. To illustrate, typical noise levels may be assigned to various environments in which the patient may be located. For example, a noise level of 30 dB SPL may be assigned to a quiet office in which the patient may be located, a noise level of 60 dB SPL may be assigned to an outdoor environment in which the patient may be located, and a noise level of 70 dB SPL may be assigned to a relatively noisy restaurant in which the patient may be located. Detection facility **304** may then detect that the user has entered one of these predetermined environments and automatically set the noise level to be equal to the noise level assigned to that environment.

AGC facility **306** may be configured to perform one or more AGC functions with respect to an audio signal detected by detection facility **304**. For example, AGC facility **306** may determine a particular sound level region in which the input sound level of the detected audio signal is located and apply a gain to the detected audio signal in accordance with an AGC gain function. The AGC gain function may be configured to specify an amount of gain that is to be applied to an audio signal by AGC facility **306** for any given input sound level. Exemplary AGC gain functions will be described in more detail below.

AGC facility **306** may be further configured to apply a gain to a detected noise signal in accordance with the AGC gain function. For example, detection facility **304** may detect a noise signal associated with an audio signal of interest. The noise signal may be subjected to the same AGC gain function to which the audio signal of interest is subjected. As will be described below, the AGC gain function may specify that a lower gain is to be applied to the noise signal than to the audio signal of interest.

In some examples, the AGC gain function used by AGC facility **306** may be adjusted, modified, or otherwise set by a user and/or automatically in response to one or more factors. For example, AGC facility **306** may adjust the AGC gain function in response to a change in a detected noise level associated with one or more audio signals presented to a patient. Examples of adjusting an AGC gain function will be described in more detail below.

Control facility **308** may be configured to perform one or more operations associated with a control of auditory prosthesis **110**. For example, control facility may be configured to direct auditory prosthesis **110** to apply electrical stimulation (e.g., to one or more stimulation sites located within an auditory prosthesis patient) representative of an audio signal detected by detection facility **304** and subjected to adaptive gain control by AGC facility **306**. To this end, control facility **308** may be configured to generate and transmit one or more control parameters (e.g., stimulation parameters) to auditory prosthesis **110**.

Storage facility **310** may be configured to maintain AGC data **312** associated with and/or used by AGC facility **306** and control parameter data **314** representative of one or more control parameters, which may include one or more stimulation parameters (e.g., current steering parameters) to be transmitted from sound processor **104** to auditory prosthesis **110**. Storage facility **310** may be configured to maintain additional or alternative data as may serve a particular implementation.

FIG. 4 illustrates exemplary components of auditory prosthesis **110**. As shown in FIG. 4, auditory prosthesis **110** may include a communication facility **402**, a power supply facility **404**, a current generation facility **406**, a stimulation facility **408**, and a storage facility **410**, which may be in communication with one another using any suitable communication technologies. Each of these facilities **402-410** may include any combination of hardware, software, and/or firmware as may serve a particular application. For example, one or more of facilities **402-410** may include a computing device or processor configured to perform one or more of the functions described herein. Facilities **402-410** will now be described in more detail.

Communication facility **402** may be configured to facilitate communication between auditory prosthesis **110** and sound processor **104**. For example, communication facility **402** may include one or more coils configured to receive control signals and/or power signals from sound processor **104**. Communication facility **402** may additionally or alternatively be configured to transmit one or more status signals and/or other data to sound processor **104**.

Power supply facility **404** may be configured to provide power to various components included within auditory prosthesis **110**. To this end, power supply facility **404** may be configured to derive a compliance voltage from a power signal received from sound processor **104**. The compliance voltage may be used by current generation facility **404** to generate stimulation current and/or by any other component within auditory prosthesis **110**.

Current generation facility **406** may be configured to generate stimulation current in accordance with one or more stimulation parameters received from sound processor **104**.

To this end, current generation facility **406** may include one or more current generators and/or any other circuitry configured to facilitate generation of stimulation current. For example, current generation facility **406** may include an array of independent current generators each corresponding to a distinct electrode or channel.

Stimulation facility **408** may be configured to facilitate application of the stimulation current generated by current generation facility **406** to one or more stimulation sites within the patient in accordance with one or more stimulation parameters received from sound processor **104**.

Storage facility **410** may be configured to maintain data generated and/or utilized by auditory prosthesis **110**. For example, storage facility **410** may maintain data representative of one or more stimulation parameters configured to define the stimulation current generated and applied by auditory prosthesis **110**.

FIG. **5** illustrates an exemplary method **500** of improving representation by an auditory prosthesis system of audio signals having intermediate sound levels. While FIG. **5** illustrates exemplary steps according to one embodiment, other embodiments may omit, add to, reorder, and/or modify any of the steps shown in FIG. **5**. One or more of the steps shown in FIG. **5** may be performed by any component or combination of components of sound processor **104**.

In step **502**, a sound processor detects an input sound level of an audio signal presented to an auditory prosthesis patient. The sound processor may detect the input sound level of the audio signal in any of the ways described herein.

In step **504**, the sound processor determines whether the detected input sound level is in a quiet region that includes input sound levels at or below a first input sound level boundary, an intermediate region that includes input sound levels above the first input sound level boundary and below a second input sound level boundary, or a loud region that includes input sound levels at or above the second input sound level boundary. The sound processor may determine which sound level region within which the detecting input sound level falls in any of the ways described herein.

In step **506**, the sound processor applies a gain to the audio signal in accordance with an AGC gain function that specifies the gain to be substantially equal to or less than a first gain threshold if the detected input sound level is in the quiet region, substantially equal to or less than a second gain threshold if the detected input sound level is in the loud region, and greater than the first and second gain thresholds if the detected input sound level is in the intermediate region. The sound processor may apply a gain to the audio signal in any of the ways described herein.

An exemplary implementation of method **500** by sound processor **104** will now be described. It will be recognized that the exemplary implementation that will be described is merely illustrative of the many different possible implementations of method **500**.

FIG. **6** shows a graph **600** illustrating an exemplary AGC gain function **602** that may be used by some sound processors to determine a gain to apply to an audio signal presented to an auditory prosthesis patient. As shown, AGC gain function **602** defines a mapping between possible input sound levels (in dB SPL) of an audio signal and corresponding gains (in dB) that may be applied to the audio signal. For example, AGC gain function **602** specifies that a gain of approximately 42 dB may be applied to audio signals having input sound levels of 20 to 60 dB SPL. However, for input sound levels greater than 60 dB SPL, AGC gain function **602** specifies that a sound processor will progressively apply less gain as the input sound level increases. In this manner, relatively loud sounds (which,

in this case, include input sound levels above 60 dB SPL) are amplified less than relatively quiet sounds (which, in this case, include input sound levels below 60 dB SPL).

However, as described above, it may be disadvantageous to linearly apply the same amount of gain to all relatively quiet input sound levels (e.g., all input sound levels less than or equal to 60 dB SPL) as specified by AGC gain function **602**. For example, an audio signal including soft speech may have an input sound level of 45 dB SPL. However, a noise level of noise associated with the audio signal may have an input sound level of approximately 30 dB SPL. In accordance with AGC gain function **602**, an equal amount of gain will be applied to the soft speech and the noise. Such amplification of the noise may drown out the soft speech and make it difficult for the patient to understand the soft speech.

Hence, in accordance with the systems and methods described herein, an AGC gain function may be set to selectively amplify audio signals having intermediate sound levels more than audio signals having relatively low sound levels (i.e., low level noise) and audio signals having relatively high sound levels (i.e., loud sounds). For example, FIG. **7** shows a graph **700** illustrating an exemplary AGC gain function **702** configured to selectively amplify audio signals having intermediate sound levels more than audio signals having relatively low sound levels and audio signals having relatively high sound levels. AGC gain function **602** is also shown in FIG. **7** for comparative purposes.

As shown, AGC gain function **702** includes first and second expansion phases **704-1** and **704-2** (collectively referred to as “expansion phases **704**”) and first and second compression phases **706-1** and **706-2** (collectively referred to as “compression phases **706**”). As used herein, an “expansion phase” refers to an input sound level range over which the slope of AGC gain function **702** is positive and a “compression phase” refers to an input sound level range over which the slope of AGC gain function **702** is negative. In the example of FIG. **7**, first expansion phase **704-1** includes input sound levels in between 30 dB SPL and 50 dB SPL, second expansion phase **704-2** includes input sound levels below 30 dB SPL, first compression phase **706-1** includes input sound levels in between 50 dB SPL and 60 dB SPL, and second compression phase **706-2** includes input sound levels above 60 dB SPL.

The points within the graph at which the various expansion and compression phases intersect may be referred to as “knee points” **708** (e.g., low knee point **708-1**, mid knee point **708-2**, and high knee point **708-3**). As will be described below, an AGC gain function (e.g., AGC gain function **702**) may be adjusted or otherwise set by adjusting or otherwise specifying a position of knee points **708** within graph **700**.

In some examples, the low and high knee points **708-1** and **708-3** may correspond to the input sound level boundaries that define the various sound level regions (e.g., the quiet, intermediate, and loud regions described herein) within which a detected input sound level may fall. To illustrate, in the example of FIG. **7**, low knee point **708-1** corresponds to an input sound level boundary of 30 dB and high knee point **708-2** corresponds to an input sound level boundary of 60 dB. Hence, the quiet region includes input sound levels at or below 30 dB SPL, the intermediate region includes input sound levels between 30 dB SPL and 60 dB SPL, and the loud region includes input sound levels at or above 60 dB SPL. It will be recognized, however, that the low and high knee points **708-1** and **708-3** do not necessarily have to correspond to the input sound level boundaries. An example of this will be described below.

The low and high knee points **708-1** and **708-3** may also correspond to the various gain thresholds described herein. For example, low and high knee points **708-1** and **708-3** both correspond to a gain threshold of approximately 42 dB. Hence, in accordance with the systems and methods described herein, the gain applied to audio signals having input sound levels within the quiet region (i.e., at or below 30 dB SPL) is less than or equal to 42 dB. Likewise, the gain applied to audio signals having input sound levels within the loud region (i.e., at or above 60 dB SPL) is also less than or equal to 42 dB. However, the gain applied to audio signals having input sound levels that fall within the intermediate region (i.e., 30-60 dB SPL) is greater than 42 dB. It will be recognized, however, that the low and high knee points **708-1** and **708-3** do not necessarily have to correspond to the gain thresholds described herein. An example of this will be described below.

Compared to AGC gain function **602**, AGC gain function **702** not only increases the amount of gain applied to sounds that fall within the intermediate region, but also compresses the sound level of sounds that fall within the quiet region. In this manner, soft speech and other audio signals of interest that fall within the intermediate region may be more readily understood by an auditory prosthesis patient.

It will be recognized that AGC gain function **702** is merely illustrative of the many different AGC gain functions **702** that may be used in accordance with the systems and methods described herein. For example, FIG. **8** shows a graph **800** illustrating another exemplary AGC gain function **802** that may be used in accordance with the systems and methods described herein. AGC gain function **602** is also shown for comparative purposes.

As shown, AGC gain function **802** may not actually compress sounds included in the quiet region (i.e., sounds that have input sound levels at or below 30 dB). Rather, AGC gain function **802** may simply maintain a constant level of amplification for such sounds in a similar manner to that of AGC gain function **602**. Another distinct feature of AGC gain function **802** is that high knee point **708-3** corresponds to a gain (i.e., a gain of approximately 47 dB) that is higher than the gain (i.e., a gain of approximately 42 dB) to which low knee point **708-1** corresponds.

In some examples, the input sound level boundaries that define the various sound level regions within FIG. **8** may still be 30 dB SPL and 60 dB SPL. In this case, the gain threshold corresponding to 30 dB SPL is approximately 42 dB and the gain threshold corresponding to 60 dB SPL is approximately 45 dB. Hence, this example illustrates an AGC gain function having a high knee point **708-3** that does not correspond to a sound level boundary or a gain threshold.

FIG. **9** illustrates another exemplary method **900** of improving representation by an auditory prosthesis system of audio signals having intermediate sound levels. While FIG. **9** illustrates exemplary steps according to one embodiment, other embodiments may omit, add to, reorder, and/or modify any of the steps shown in FIG. **9**. One or more of the steps shown in FIG. **9** may be performed by any component or combination of components of sound processor **104**.

In step **902**, a sound processor detects a noise level associated with an audio signal presented to an auditory prosthesis patient. The sound processor may detect the noise level in any of the ways described herein.

In step **904**, the sound processor dynamically adjusts an AGC gain function in accordance with the detected noise level. The AGC gain function may be dynamically adjusted in any of the ways described herein.

In step **906**, the sound processor applies a gain to the audio signal in accordance with the dynamically adjusted AGC gain function. The gain may be applied to the audio signal in any of the ways described herein.

An exemplary implementation of method **900** by sound processor **104** will now be described. It will be recognized that the exemplary implementation that will be described is merely illustrative of the many different possible implementations of method **900**.

In some examples, an AGC gain function may be initially set to be equal to AGC gain function **702**, as described above in connection with FIG. **7**. One or more audio signals presented to an auditory prosthesis patient may be subjected to AGC gain function **702**. Subsequently, sound processor **104** may detect a change in a noise level associated with the audio signals being presented to the auditory prosthesis patient. For example, sound processor **104** may detect that the user has moved from a relatively quiet environment to a relatively loud environment and that the noise floor has increased from approximately 30 dB SPL to 40 dB SPL. In response to the increased noise level, sound processor **104** may dynamically adjust AGC gain function **702** by adjusting one or more characteristics of AGC gain function **702**. For example, sound processor **104** may dynamically adjust AGC gain function **702** to account for the increased noise level by decreasing a range of expansion phase **704-1**.

To illustrate, FIG. **10** shows an adjusted AGC gain function **1002** that may be derived by decreasing a range of expansion phase **704-1** of AGC gain function **702** (also illustrated in FIG. **10** for comparative purposes). As shown, adjusted AGC gain function **1002** includes an expansion phase **1004-1** that has a decreased range with respect to expansion phase **704-1** of AGC gain function **702**. Expansion phase **704-1** may be adjusted by repositioning one or more knee points of AGC gain function **702** and/or in any other manner as may serve a particular implementation. For example, FIG. **10** shows that an input sound level positioning of low knee point **708-1** has been increased from 30 dB SPL to 40 dB SPL (as illustrated by low knee point **1008-1**). FIG. **10** also shows that a gain positioning of mid knee point **708-2** has been decreased from 50 dB to approximately 47 dB (as illustrated by mid knee point **1008-2**). Mid knee point **708-2** may be adjusted in this manner in order to keep a slope of expansion phase **1004-1** within a predetermined limit. High knee point **708-3** has not been adjusted, as illustrated by high knee point **1008-3**.

Adjusting AGC gain function **702** in the manner illustrated in FIG. **10** may prevent the increased noise level from being amplified as much as audio signals of interest within the intermediate region. In this manner, the auditory prosthesis patient may more easily understand soft speech and other intermediate sound level sounds.

Alternatively, sound processor **104** may detect a change in a noise level associated with the audio signals being presented to the auditory prosthesis patient. For example, sound processor **104** may detect that the user has moved from an environment having a noise floor of 30 dB SPL to an environment having a noise floor of 25 dB SPL. In response to the decreased noise level, sound processor **104** may dynamically adjust AGC gain function **702** by adjusting one or more characteristics of AGC gain function **702**. For example, sound processor **104** may dynamically adjust AGC gain function **702** to account for the decreased noise level by decreasing a range of expansion phase **704-1**.

To illustrate, FIG. **11** shows an adjusted AGC gain function **1102** that may be derived by increasing a range of expansion phase **704-1** of AGC gain function **702** (also illustrated in FIG. **11** for comparative purposes). As shown, adjusted AGC

gain function **1102** includes an expansion phase **1104-1** that has an increased range with respect to expansion phase **704-1** of AGC gain function **702**. Expansion phase **704-1** may be adjusted by repositioning one or more knee points of AGC gain function **702** and/or in any other manner as may serve a particular implementation. For example, FIG. **11** shows that an input sound level positioning of low knee point **708-1** has been decreased from 30 dB SPL to approximately 25 dB SPL (as illustrated by adjusted low knee point **1108-1**). Knee points **708-2** and **708-3** remain unchanged, as illustrated by knee points **1108-2** and **1108-3**. Adjusting AGC gain function **702** in the manner illustrated in FIG. **11** may facilitate increased understanding of especially low sound level audio signals of interest.

It will be recognized that the adjustments of AGC gain function **702** as illustrated in FIGS. **10-11** may be subject to compliance with predetermined signal-to-noise ratio thresholds, one or more noise characteristics, and/or any other limitation as may serve a particular implementation.

Sound processor **104** (i.e., AGC facility **306**) may be configured to transition between applying different gains to different incoming audio signals in accordance with a syllabic compressor heuristic, a slow compressor heuristic, or a dual loop compressor heuristic (i.e., a combination of syllabic and slow compressor heuristics) as may serve a particular implementation. Syllabic compression follows the syllabic rate (e.g., 4 Hz). Slow compression is relatively slower (e.g., at the sentence level). In some examples, sound processor **104** may use the syllabic compressor heuristic for sound levels that fall within an expansion range of an AGC gain function and the dual loop compressor heuristic for sound levels that fall within a compression range of an AGC gain function.

In some examples, an AGC gain function may be specific to a particular channel or subset of channels included in a plurality of channels associated with auditory prosthesis **110**. In such instances, one or more other channels included in the plurality of channels may each be associated with a different AGC gain function than the AGC gain function specific to the particular channel. For example, a first AGC gain function may be associated with a first subset of channels included in a plurality of channels associated with auditory prosthesis **110** and a second AGC gain function may be associated with a second subset of channels included in the plurality of channels.

Alternatively, the same AGC gain function may be used for each channel within a plurality of channels. For example, the same AGC gain function may be used for each channel included in a plurality of channels associated with a particular signal processing strategy or for a subset of channels included in the plurality of channels associated with the particular signal processing strategy.

In yet another alternative embodiment, multiple channels may be related or coupled one to another. For example, AGC facility **306** may average in (e.g., with lower weighting) or otherwise include input sound levels (i.e., energy) from channels adjacent to a particular channel when applying an AGC gain function to the input sound level of the particular channel. Additionally or alternatively, AGC facility **306** may not allow the gains in adjacent channels to be different by more than a predetermined threshold. In this manner, an auditory prosthesis patient may more effectively perceive and/or understand the sounds associated with the adjacent channels.

In the preceding description, various exemplary embodiments have been described with reference to the accompanying drawings. It will, however, be evident that various modifications and changes may be made thereto, and additional embodiments may be implemented, without departing from

the scope of the invention as set forth in the claims that follow. For example, certain features of one embodiment described herein may be combined with or substituted for features of another embodiment described herein. The description and drawings are accordingly to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

**1.** A system comprising:

a detection facility that detects an input sound level of an audio signal presented to an auditory prosthesis patient; and

an adaptive gain control (“AGC”) facility communicatively coupled to the detection facility and that

determines whether the detected input sound level is in a quiet region that includes input sound levels at or below a first input sound level boundary, an intermediate region that includes input sound levels above the first input sound level boundary and below a second input sound level boundary, or a loud region that includes input sound levels at or above the second input sound level boundary, and

applies a gain to the audio signal in accordance with an AGC gain function that specifies the gain to be substantially equal to or less than a first gain threshold if the detected input sound level is in the quiet region, substantially equal to or less than a second gain threshold if the detected input sound level is in the loud region, and greater than the first and second gain thresholds if the detected input sound level is in the intermediate region.

**2.** The system of claim **1**, wherein the application of the gain to the audio signal results in an amplified audio signal, and wherein the system further comprises a control facility communicatively coupled to the AGC facility and that directs an auditory prosthesis to apply electrical stimulation representative of the amplified audio signal.

**3.** The system of claim **1**, wherein:

the detection facility further

detects an input sound level of an additional audio signal presented to the auditory prosthesis patient, and detects a noise level associated with the additional audio signal; and

the AGC facility further

dynamically adjusts the AGC gain function in accordance with the detected noise level, and

applies a gain to the additional audio signal in accordance with the dynamically adjusted AGC gain function.

**4.** The system of claim **1**, wherein the AGC gain function: defines a mapping between a plurality of input sound levels and a plurality of gains; and

comprises an expansion phase within the intermediate region and a compression phase within the loud region.

**5.** The system of claim **4**, wherein the expansion phase and the compression phase meet within the intermediate region.

**6.** The system of claim **4**, wherein the AGC gain function further comprises an additional expansion phase within the quiet region.

**7.** The system of claim **4**, wherein the AGC facility further uses a syllabic compressor heuristic during the expansion phase.

**8.** The system of claim **4**, wherein the AGC facility further uses a dual loop heuristic during the compression phase.

**9.** The system of claim **1**, wherein the AGC gain function is specific to a particular channel included in a plurality of channels associated with an auditory prosthesis communicatively coupled to the system, and wherein one or more other

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channels included in the plurality of channels are each associated with a different AGC gain function than the AGC gain function specific to the particular channel.

10. The system of claim 1, wherein the AGC gain function is associated with each channel included in a plurality of channels associated with an auditory prosthesis communicatively coupled to the system.

11. The system of claim 1, wherein the AGC gain function is associated with a first subset of channels included in a plurality of channels associated with an auditory prosthesis communicatively coupled to the system and another AGC gain function is associated with a second subset of channels included in the plurality of channels.

12. The system of claim 1, wherein the second gain threshold is greater than the first gain threshold.

13. A system comprising:

- a detection facility that detects a noise level associated with an audio signal presented to an auditory prosthesis patient; and
- an adaptive gain control (“AGC”) facility communicatively coupled to the noise detection facility and that dynamically adjusts an AGC gain function in accordance with the detected noise level, and applies a gain to the audio signal in accordance with the dynamically adjusted AGC gain function.

14. The system of claim 13, wherein the noise level corresponds to a noise signal associated with the audio signal, and wherein the AGC facility further applies a gain to the noise signal in accordance with the dynamically adjusted AGC gain function.

15. The system of claim 13, wherein the detection facility detects the noise level associated with the audio signal by: detecting an environment in which the auditory prosthesis patient is located; and setting the noise level to be equal to a predetermined noise level associated with the detected environment.

16. The system of claim 13, wherein:

- the detected noise level is higher than a previously detected noise level; and
- the AGC facility dynamically adjusts the AGC gain function by decreasing a range of an expansion phase included in the AGC gain function.

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17. The system of claim 13, wherein: the detected noise level is lower than a previously detected noise level; and

the AGC facility dynamically adjusts the AGC gain function by increasing a range of an expansion phase included in the AGC gain function.

18. A method comprising:

- detecting, by a speech processor, an input sound level of an audio signal presented to an auditory prosthesis patient;
- determining, by the speech processor, whether the detected input sound level is in a quiet region that includes input sound levels at or below a first input sound level boundary, an intermediate region that includes input sound levels above the first input sound level boundary and below a second input sound level boundary, or a loud region that includes input sound levels at or above the second input sound level boundary; and

applying, by the speech processor, a gain to the audio signal in accordance with an adaptive gain control (“AGC”) gain function that specifies the gain to be substantially equal to or less than a first gain threshold if the detected input sound level is in the quiet region, substantially equal to or less than a second gain threshold if the detected input sound level is in the loud region, and greater than the first and second gain thresholds if the detected input sound level is in the intermediate region.

19. The method of claim 18, wherein the applying of the gain to the audio signal results in an amplified audio signal, and wherein the method further comprises directing, by the speech processor, an auditory prosthesis to apply electrical stimulation representative of the amplified audio signal.

20. The method of claim 18, further comprising:

- detecting, by the speech processor, an input sound level of an additional audio signal presented to the auditory prosthesis patient;
- detecting, by the sound processor, a noise level associated with the additional audio signal;
- dynamically adjusting, by the speech processor, the AGC gain function in accordance with the detected noise level; and
- applying, by the speech processor, a gain to the additional audio signal in accordance with the dynamically adjusted AGC gain function.

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